The CERES S'COOL Project: Data Product Intercomparison

Amanda Falcone
Trinity University, San Antonio, TX
Mentor: Dr. Lin Chambers
Atmospheric Sciences Competency
Radiation and Aerosols Branch

Abstract

The CERES (Clouds and the Earth's Radiant Energy System) project will provide data over an expected span of 15 years that will lead to better understanding of the role of clouds in the Earth's energy cycle and in global climate change. Understanding clouds, where they occur, and their characteristics are important keys to understanding global climate changes. The S'COOL (Students' Cloud Observations On-Line) project is an integral aspect of the validation of CERES. In the S'COOL project over 900 schools from around the globe provide information about clouds from the ground as the CERES instrument orbits overhead on a satellite. This "ground truth" provides one method of ensuring that the instruments are functioning properly and clearly identifying all of the clouds. Two data products from CERES are examined in this study: the SSF (single scanner footprint) using cloud data from the VIRS (Visible Infrared Scanner) and the ES8, an ERBE-like (Earth Radiation Budget Experiment-like) product. These two datasets are compared with the ground dataset from the S'COOL project using statistical analysis in order to compare the level of agreement between the datasets. The comparison of these data products will help to validate the CERES data, and aid in a better understanding of the shortcomings of current forms of measurement.

"…the science of Nature has been already too long made only a work of the brain and the fancy;
It is now high time that it should return to the plainness and soundness of observations…"
- Robert Hooke (1635-1703)

1 Introduction

The Clouds and the Earth's Radiant Energy System (CERES) project is one of the highest priority undertakings of NASA Langley Research Center's Atmospheric Sciences research (CERES homepage, 2001). CERES is part of the Earth Observing System (EOS), an international program developed to study Earth from space using a multi-instrument, multi-satellite approach (EOS homepage, 2001). The purpose of CERES is to develop a better understanding of the role of clouds in the Earth's energy cycle and their relationship with possible global climate change. CERES data will build on previously collected data from experiments such as the Earth Radiation Budget Experiment (ERBE) (ERBE homepage, 2001). All of these data together will enable scientists to develop more accurate climate models with proper modeling of the effects of clouds on global climate change. It is important to understand the effects of clouds on the Earth's climate in order to understand the effects they might have on global warming or global cooling trends.

Clouds play a major role in determining the climate of the Earth (CERES Brochure, 1999). The sun provides the radiant electromagnetic energy that fuels the Earth's climate in the form of visible (shortwave) radiation. In turn, the Earth radiates energy back to space, mainly in the form of infrared (longwave) radiation. One of the many functions of the atmosphere is to maintain a balance between energy received from the sun and energy radiated from the Earth. The energy balance between incoming and outgoing radiation is known as the Earth's radiation budget.

Many factors affect the energy budget, and some are much more predictable than others. Important components in determining the radiation budget are the planet's surface, atmosphere, and clouds present in the atmosphere. It is relatively simple to determine the type of land at the surface and the composition of the atmosphere; but because of the ever-changing nature of clouds, it is difficult to predict the composition of the clouds at any time in any particular location. The difference between clear-sky and all-sky radiation results is known as cloud-radiative forcing, and this is a measure of the effect that clouds have on the Earth's radiation balance. One of the purposes of CERES is to become better able to characterize clouds in all areas of the world, in order to account for the effects of cloud-radiative forcing in climate models.

In order to have accurate data from CERES and other satellite missions, it is important to have properly calibrated instruments and ensure that these instruments are functioning correctly. The CERES Students' Cloud Observations On-Line (S'COOL) project is an educational outreach effort that aids in the validation of the cloud measurements made by the CERES instrument (S'COOL Homepage, 2001). Schools from around the globe register online or through the mail with the S'COOL project, and then make ground observations of the clouds as a CERES instrument passes overhead on a satellite. Currently over 900 schools from over 55 different countries take data to be used for comparison with CERES data. The "ground truth" data provided by these schools is then compared with the data recorded by the CERES instrument. Several attributes of the clouds are recorded for comparison; however in this study only cloud fraction, the amount of clouds present in the sky at the given time, is considered. The focus of this study is the comparison of the S'COOL ground truth data with two different CERES data products, the pre-Single Scanner Footprint (SSF) using cloud data from the Visible/Infrared Scanner (VIRS) and the ES8, an Earth Radiation Budget Experiment-like

(ERBE-like) product. From these comparisons it is possible to better understand the satellite data and to understand where the strengths and shortcomings of each type of product arise.

2 S'COOL Data

The S'COOL project was developed in a phased manner over more than a year, starting in January 1997. Several changes have been made to the report form since the early time period. As a result, the database entries in the 1997-1998 time frame have some problems that require human intervention to resolve. Many of these formatting problems have been manually repaired, but a small number linger in imperfect form. There are also a number of duplicate entries, whether from the participants accidentally entering a single observation more than once or from problems with the database recording program. Most of these duplicates have been manually removed; but a few with different cloud records remain unresolved.

The majority of data provided by the participating schools in the S'COOL project are collected electronically via the Internet. When the class makes an observation, the data are then entered through the S'COOL website and recorded in the S'COOL database at the Atmospheric Sciences Data Center (ASDC) – formerly known as the Distributed Active Archive Center (DAAC). Some data are also sent by mail or fax and entered into the database by the S'COOL project team. All of the S'COOL entries are stored in the database at the ASDC, however, and it is from there that the data are extracted for use.

The students in the schools record a number of different pieces of information about the clouds at the time of observation. These include: the cloud fraction, cloud type, cloud opacity, and various other measurements, including temperature, pressure, and others. The focus of this study is the cloud fraction measurement. The clouds are classified as clear, partly cloudy, mostly cloudy, or overcast according to how much sky is covered by the clouds at the given time. The break points between clear and partly cloudy, partly cloudy and mostly cloudy, and mostly cloudy and overcast were created according to the classifications that were present on ERBE. The clear classification is used when the sky is 0-5% cloudy, partly cloudy is 5-50% cloudy, mostly cloudy is 50%-95% cloudy, and overcast is classified as 95-100% cloudy. The ground reports are compared with the satellite results in this study.

3 CERES Data

CERES instruments are currently orbiting the Earth on two satellites, and there are three instruments that have yet to be launched. The Tropical Rainfall Measuring Mission (TRMM) satellite carries the ProtoFlight Model (PFM) CERES, while the Terra satellite, which is a part of the EOS, carries Flight Model 1 (FM1) and Flight Model 2 (FM2). The Aqua satellite, which is scheduled to be launched in 2002, will carry Flight Model 3 (FM3) and Flight Model 4 (FM4). Flight Model 5 (FM5) does not currently have a satellite carrier identified. (TRMM homepage, Terra Homepage, Aqua Homepage, 2001)

The CERES instrument itself is superior to previous similar instruments in many different aspects of measurement. CERES contains three scanning thermistor bolometer radiometers that measure the radiation in the near-visible through the far-infrared spectral region. The shortwave detector measures the Earth-reflected and Earth-emitted shortwave radiation while the Earth-emitted longwave is measured by the window detector in the water vapor window. The total Earth-emitted and Earth-reflected radiation is measured by the total detector. The detectors are

coaligned and mounted on a spindle that rotates about the instrument elevation axis. (CERES On-Line Documentation, 2001). The specific details of CERES data collection and the algorithms involved can be found in Wielicki *et al.*, 1998.

4 Results

Multiple comparisons between the CERES data products and the S'COOL database have been performed using programs written in FORTRAN 90. Through these comparisons, it is possible to draw conclusions as to the accuracy of the interpretations of the CERES instrument's measurements. It is also possible to see examples of the intrinsic errors that are present within the data products, and to better understand how to interpret the data from the instrument.

4.1 Single Scanner Footprint (SSF) Data

The Single Scanner Footprint (SSF) is a product from CERES containing one hour of data that is developed from the combined CERES instrument data and information from a higher resolution imager. The data used in this comparison is the intermediate product from the imager that is used to produce the SSF; it will hereafter be referred to as the SSF. Examples of these imagers are the Visible/Infrared Scanner (VIRS) on the TRMM satellite and the Moderate-Resolution Imaging Spectroradiometer (MODIS) on Terra and Aqua satellites. The SSF contains information about clouds that includes the cloud amount, height, temperature, pressure, optical depth, emissivity, ice and liquid water path, and water particle size. Also within the SSF are the CERES filtered radiances for the total, shortwave (SW), and window (WN) channels and the unfiltered SW, longwave (LW), and WN radiances. These radiances are taken at spacecraft altitude and converted to TOA fluxes, which are then used to estimate surface fluxes.

TRMM was launched in November 1997. Before TRMM was launched, various other instruments on assorted satellites were taking data similar to the data taken by VIRS on TRMM and was used in the development of S'COOL. This data will hereafter be referred to as pre-TRMM data. On TRMM, CERES uses the VIRS imager, which has 2.11 km spatial resolution at nadir and a deployable solar diffuser plate to monitor long term instrument gain stability. VIRS is a five-channel imaging spectroradiometer that measures the radiation in distinct visible through infrared spectral bands. The Earth-reflected shortwave radiation is measured through the shortwave channels, 0.63 μm and 1.61 μm, while the Earth-emitted longwave radiation is measured in three channels, 3.78 μm, 10.8 μm, and 12.0 μm. More details of the SSF product can be found in the CERES SSF Collection Guide. (CERES Online Documentation, 2001). It is important to consider when using this data set that the CERES instrument on TRMM failed at the end of 1998, therefore limiting the amount of data available for comparison. After the month of August 1998, there is little data that is acceptable for use, therefore the number of matches between the S'COOL data and SSF data are smaller than would otherwise be expected.

The SSF data are contained in a large database at the ASDC. This database is used for comparison with the S'COOL database. In the pre-TRMM and TRMM time period, there are 91 total matches between the students' observations and the measurements made by the satellite instrument. The comparison can be seen in Table 4.1.1. The table is arranged with the satellite measurements running down and the ground measurements running across the top. The measurements are compared if the ground site (school) is located within the one degree grid in which the satellite is recording data and the time the satellite passes over is within 15 minutes of

when the ground observation is made. Each instance when the satellite records clear sky and the ground observers also record clear sky, a count is added to the corresponding box in the table. This is classified as "Agree" because the satellite and the ground have exact agreement. Occasions when the measurements are one class separated from the other, such as when the satellite records partly cloudy and the ground records clear, are recorded as "1-class" errors and similarly for "2-class" and "3-class" errors. Exact matches between the imager and the ground observers occur most often. In order to verify that these matches were not completely by chance, a statistical analysis method known as "Chi Squared" (χ^2) is performed on the table, and from this analysis it is possible to develop a probability of occurring by chance. In this case, the probability that this level of agreement would occur by chance is $1.37*10^{-19}$%.

Table 4.1.1 – Overall SSF Comparison (1997-1999)

		Ground			
		Clear	Partly Cloudy	Mostly Cloudy	Overcast
Satellite	Clear	27	2	2	0
	Partly Cloudy	6	10	2	1
	Mostly Cloudy	5	2	11	6
	Overcast	0	1	5	11

Total Number of Matches = 91

Summary of Errors:
Agree: 58   1-class: 23   2-class: 9   3-class: 1
Agree and 1-class: 81   2-class and 3-class: 10
Statistical Analysis:
$\chi^2 = 119.94$ Significance = $1.37*10^{-19}$%

Note that when the "Agree" and "1-class" levels of agreement are added together, they make up 81 of the 91 matches, or 89.0% of the total. This leaves ten "2-class" and "3-class" matches, or 11% of the total. The "Agree" category itself consists of 64% of the total matches, which in itself is a fairly high level of agreement and is comparable to previous satellite intercomparisons.

4.2 ES8 Data

The ES8 (ERBE-like Science Product #8) is a product from the CERES instrument which is processed in the same manner as the data from ERBE. This is in order to have consistent data from the 1980s through the present. By processing the new data in the same manner as the older data (though that process is not as specialized or refined as newer methods) it is possible to look for trends in the data that would not be understandable without consistency in the processing. The ES8 product contains 24 hours of instantaneous CERES data for a single instrument, and does not rely on imager data. Measurements of the shortwave, longwave, and total radiances of the atmosphere are entered into a scene identification model and Angular Distribution Models (ADMs) which are identical to those used for ERBE. The ES8 dataset then contains the TOA fluxes, scene identification, and angular geometry. The portion of the ES8 used in this study is the scene identification (ID), which gives an indication of cloud fraction.

The scene ID of the ES8 is created using a Maximum Likelihood Estimator (MLE), which is a bi-spectral identifier of cloud cover where clouds are characterized as cold and bright.

Clouds are typically much colder than the land below them, and they are typically much brighter than land as well. Therefore, the MLE takes this into account when determining scene identification. To classify a CERES observation, initially the 2.5° region that contains the scanner TOA point is identified. Then from a priori physical landform data, the geographic scene is determined as ocean, land, snow, desert, or land-ocean mix. The cloud condition is then determined using the MLE for that particular type of region. Figure 4.2.1 is an example of a typical scene identification using the MLE.
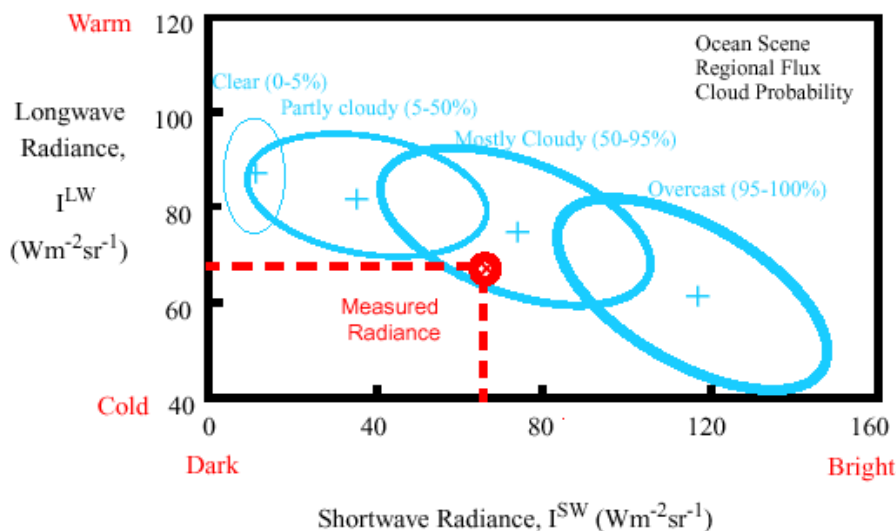

Figure 4.2.1 – ERBE Scene Identification Algorithm

From this algorithm it is possible to obtain an indication of how much cloud is present in the atmosphere at the time the satellite passes over. This method of scene identification is, however, somewhat coarse. Because the only method of measurement is through longwave and shortwave radiances, it is possible to misidentify certain classes of clouds. Typically, high, thin, overcast, cirrus-type clouds, while overcast, are more transparent than other overcast clouds, and therefore appear warmer and darker to the satellite than an overcast convective cloud would appear. Therefore, overcast cirrus-type clouds are often mis-classified as mostly cloudy as opposed to overcast. Similarly, isolated deep convective clouds can appear to be clear (0-5% cloudy) from the ground, but the satellite would classify them as partly cloudy. If even only 4% of the sky is covered by convective clouds, their tendency to be colder and brighter than other clouds would lead the ES8 to incorrectly identify them.

With these inherent problems in mind, the ES8 data are compared with the S'COOL database in the same manner as the SSF. Table 4.2.1 shows the results. The level of agreement is less than that found with the SSF, with only 27% matching. When the data are examined more closely it can be seen that the majority of shifts in this table compared to the SSF table are from satellite recording clear to satellite recording partly cloudy when the ground records clear; and from satellite recording overcast to satellite recording mostly cloudy while the ground records overcast. This is somewhat expected, as MLE would cause a shift of this nature, as discussed above. However, the "Agree" and "1-class" errors together consist of 66 of the 71 total matches, which is 93.0%; while the "2-class" and "3-class" errors consist of 5 of the 71 matches, which is 7.0%. These values are comparable with the SSF values for this level of agreement. It is difficult, however, to make any strong statements at this point, because these two tests contain

different observations. The next section of this report presents a one-to-one comparison between the ES8 and the SSF datasets.

Table 4.2.1 – Overall ES8 Comparison (January – August 1998)

		Ground			
		Clear	Partly Cloudy	Mostly Cloudy	Overcast
Satellite	Clear	5	2	0	0
	Partly Cloudy	16	4	7	2
	Mostly Cloudy	1	3	4	17
	Overcast	1	1	2	6

Total Number of Matches = 71

Summary of Errors:

Agree: 19   1-class: 47   2-class: 4   3-class: 1

Agree and 1-class: 66   2-class and 3-class: 5

Statistical Analysis:

$\chi^2 = 48.90$ Significance $= 1.73*10^{-5}$%

4.3 SSF Data versus ES8 Data

In order to understand how the SSF and ES8 comparisons relate to each other, it is necessary to perform a one-to-one analysis of the two comparisons. This involves identifying the points where there is a match between the SSF data and the S'COOL data, and comparing this to the exact same S'COOL site at the same time with the ES8 dataset. There are fewer matches when this one-to-one analysis is performed, as it covers only the TRMM time period, but there are enough matches to illustrate the differences between the two methods of comparison.

Table 4.3.1 is the SSF compared with the ground data while table 4.3.2 is the ES8 compared with the ground data. These two comparisons are one-to-one with each other, that is, for every ground to satellite match with the SSF; there is a corresponding ground to satellite match with the ES8. This allows for an exact analysis of one comparison with the other.

In the SSF versus ground comparison there is again a large degree of exact agreement, with the number of matches decreasing with the class of error. There are no third class errors in this table. The "Agree" and "1-class" errors make up 92.3% of the total matches, while the "2-class" and "3-class" errors are the remaining 7.7%. This is consistent with the percentages when the entire data set was compared. It should also be noted that the χ^2 value of this table is 32.75, which yields a probability of occurring by chance of 0.015%. This indicates, even with such a small sample size, that the ground contributes valuable information.

In the ES8 versus ground comparison, it is tempting to note that the "Agree" and "1-class" errors compose 88.5% of the total matches while the "2-class" and "3-class" errors make up the remaining 11.5%. These numbers are consistent with the SSF comparison, as well as earlier ES8 comparisons. Therefore, if the "Agree" and "1-class" errors are taken to be "reasonable" matching, the ES8 comparison is on par with the SSF comparison. However, upon closer comparison it can be seen that the majority of the ES8 comparison is comprised of "1-class" errors, and that there is a definite shift in the levels of agreement. When the ground records clear, the ES8 more often records partly cloudy; and when the ground reports overcast, the ES8 more often records mostly cloudy. Upon further investigation it is determined that the

majority of these instances are explicable, with the explanations detailed below. The χ^2 value of this table is only 17.40, which indicates that the probability of occurring by chance of this particular table is 4.28%. While still a small number, this indicates that the ES8 is not as appropriate for comparisons of ground observed cloud fraction as the SSF. If the SSF comparison is taken to be the truth, then it is possible to analyze how the comparison has shifted from the SSF to the ES8. Table 4.3.3 demonstrates the movement between the comparison for SSF to the comparison for the ES8.

Table 4.3.1 – SSF Comparison (Ground vs. Satellite)

		Ground			
		Clear	Partly Cloudy	Mostly Cloudy	Overcast
Satellite	Clear	6	1	1	0
	Partly Cloudy	1	2	1	0
	Mostly Cloudy	1	1	3	2
	Overcast	0	0	3	4

Total Number of Matches = 26

Summary of Errors:
Agree: 15   1-class: 9   2-class: 2   3-class: 0
Agree and 1-class: 24   2-class and 3-class: 2
Statistical Analysis:
$\chi^2 = 32.75$ Significance = 0.015%

Table 4.3.2 – ES8 Comparison (Ground vs. Satellite)

		Ground			
		Clear	Partly Cloudy	Mostly Cloudy	Overcast
Satellite	Clear	2	3	0	0
	Partly Cloudy	5	2	2	0
	Mostly Cloudy	1	0	1	5
	Overcast	0	1	2	2

Total Number of Matches = 26

Summary of Errors:
Agree: 7   1-class: 16   2-class: 2   3-class: 1
Agree and 1-class: 23   2-class and 3-class: 3
Statistical Analysis:
$\chi^2 = 17.40$ Significance = 4.28%

Table 4.3.3 – SSF Comparison vs. ES8 Comparison Changes in Location

		Ground			
		Clear	Partly Cloudy	Mostly Cloudy	Overcast
Satellite	Clear	‖	|		
	Move	↓↓↓↓	↑↓		
	Partly Cloudy		‖	|	
	Move		↑	↑	↑
	Mostly Cloudy	|		|	
	Move			↓	↑↑↑↓
	Overcast			‖‖	|

From this table it is possible to determine in a one-to-one sense exactly what the differences between the SSF comparison and the ES8 comparison are. Each mark on the table represents a single ground observation. If it is a single line (|), it represents an instance when the SSF and ES8 record the same amount of cloudiness. The upward pointing arrows (↑) represent the instances in which the ES8 records a smaller level of cloudiness than the SSF. The downward pointing arrows (↓) represent the occasions when the ES8 records a greater level of cloudiness than the SSF. In the cases in which the arrows are present, the arrow is placed in the "Move" category between the two levels of cloudiness. The start of the arrow is pointed at the level of cloudiness recorded by the SSF, while the end of the arrow (point) is directed to the level of cloudiness observed by the ES8. It can be seen that the majority of movement occurs between satellite recording clear to satellite recording partly cloudy, as well as from satellite recording overcast to satellite recording mostly cloudy. Preliminary analysis of March 2000 data from the CERES instrument on Terra shows the same patterns.

The four occasions in which the satellite reading moved from clear to partly cloudy are similar. Two occasions are from the city of Danville, VA, where the students recorded completely clear. The SSF also recorded clear, but the ES8 recorded partly cloudy. The same situation is found in Prince George, VA. Similar, but not identical, is the situation of Bluefield, VA, in which the ground reports translucent cirrus clouds that fill 0-5% of the sky. There are many possible explanations for these discrepancies. One probable reason for the discrepancies between the two satellite measurements is the conservative nature of the ES8 measurement. The ERBE scene identification algorithm tends to be very restrictive when deciding between clear and partly cloudy. In order for the scene to be classified as clear, the land albedo must be low and the temperature must be warm.

When the change is from satellite overcast to satellite mostly cloudy, there are several different possibilities due to the very different nature of the four occurrences. In one instance, the students in Danville, VA recorded opaque cirrus type clouds covering 95-100% of the sky, in which case the SSF recorded overcast while the ES8 recorded mostly cloudy. This is due to the nature of cirrus clouds which are more transparent than other types of clouds, and therefore the tendency of these clouds to appear warmer, which leads the ERBE-like processing to place them in the mostly cloudy category. A second instance of the SSF recording more cloudiness than the ES8 occurs in Danville, VA. In this case, the ground observers report opaque nimbostratus clouds covering 95-100% of the sky. However, upon further investigation it is found that the SSF records this cloud as being fairly thin and warm. This would be enough of a factor for the ES8 classification algorithm to place the cloud in the mostly cloudy rather than the overcast category. In the final two instances, the discrepancy between satellite instruments is due simply to the manner in which the data are processed. In these instances the ground observers reported multiple layers of cloudiness, and multiple layers of cloudiness are measured by the SSF. However, the ES8 is unable to measure cloud layers. When the percentage of cloudiness per layer for the SSF is added up to a single cloud fraction, the assumption is being made that there is no overlap of cloud cover and that each cloud layer is fully independent of the other. In fact, the cloud cover is most likely somewhere between completely independent layers and completely overlapping layers (which would involve taking the largest layer as the entire cloud cover). Because of the manner in which the cloud cover is calculated, it is conceivable that the cloud cover is between 90-100% cloudy, and the classification is what leads to the discrepancies

between the SSF measurement and the ES8 measurement. These one-to-one comparisons illustrate the differences between the SSF and ES8 data products.

5 Conclusion

To fully understand the measurements registered by satellite instruments, it is important to have some kind of validation process. The CERES S'COOL project provides one data set that can be used for validating the satellite measurements. Through this study of the SSF comparison versus the ES8 comparison to the ground data, it is possible to understand the intrinsic flaws in each measurement, as well as to better understand the data as it is presented. It is possible to see that the CERES instrument has superior cloud ID capacities that were not present with ERBE.

Understanding the issues that arise when interpreting data will aid in a better understanding of the actual amounts of cloud cover, and therefore make it possible to create more accurate cloud models. For instance, knowing that the ERBE-like process will lead to slightly skewed data will not only allow the current data to be interpreted correctly, but it will also provide future researchers with the understanding of how to modify identification algorithms in order to provide more accurate pictures of the sky. Having a ground perspective to compare to the sky observations ensures that a more genuine picture of the sky will be created. This ground truth data provides a greater understanding of the problems that can arise with satellite-only measurements. This will enable more precise cloud observations to be made with unprecedented accuracy. This new accuracy will lead to more accurate global climate models.

As all instruments and the S'COOL schools continue to take data, the number of matches in the comparisons will continue to grow. This study has led the CERES/S'COOL team to make plans to include both SSF results and ES8 results (which are available sooner because they do not require imager data) to be placed in the S'COOL database for comparison to ground observations. The comparisons presented in this paper will allow proper interpretation of the different results.

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